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DYNAMIC VARIABLE VOLUME SAMPLING METHOD FOR DETERMINING MASS EMISSIONS OF POLLUTING SUBSTANCES WITH EXHAUST GASES

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Представлено результати розроблення і дослідження перспективного повно-потокового динамічного методу відбору проб змінного об‘єму для визначення в лабораторних умовах значень масових викидів забруднювальних речовин з відпрацьованими газами автомобільних двигунів. Викиди визначають за процедурами випробування повнокомплектних автомобілів в їздових циклах, або окремо їх двигунів за моторними випробувальними циклами.

Поточні масові викиди забруднювальних речовин розраховують за синхронізованими у часі миттєвими значеннями їх концентрацій та миттєвими значеннями витрати потоку суміші відпрацьованих газів і повітря. До змішувальної камери, до якої подають відпрацьовані гази і повітря, також подають повірочну газову суміш з витратою, що змінюють за періодичною функцією. Це використовують для визначення передаточних функцій зворотного обчислення миттєвої витрати суміші відпрацьованих газів і повітря та поточних значень концентрацій забруднювальних речовин в момент відбору проби. Масові викиди газоподібних забруднювальних речовин розраховують як різницю між сумарними масовими викидами забруднювальних речовин та масовими викидами забруднювальних речовин, що додають з потоком повірочної газової суміші.

Працездатність динамічного повно-потокового метода відбору проб змінного об'єму доведено порівнянням розрахункової (методом балансу вуглецю) та безпосередньо виміряної витрати палива автомобілями в їздових циклах. Різниця між безпосередньо виміряною та розрахунковою (за визначеними масовими викидами забруднювальних речовин) витратою палива не перевищує ±3,5 %. Це є задовільним результатом з огляду на, зокрема, невизначеність вимірювання в динаміці швидкозмінних концентрацій забруднювальних речовин, витрати потоку розбавлених ВГ, витрати палива, а також визначення вмісту вуглецю у паливі.

Отримано принципово нові можливості з вимірювання масових питомих викидів забруднювальних речовин двигунами з примусовим запалюванням та дизелів сучасних (екологічного класу «Євро-6») і перспективних транспортних засобів з низьким рівнем емісії

Ключові слова: відпрацьовані гази, масові викиди забруднювальних речовин, constant volume sampling, CVS, variable volume sampling, VVS

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1. Introduction

Road transport is the dominant source of pollution by toxic substances of atmospheric air in places of mass concentration of the population. This leads to the introduction by countries of the world of stricter standards for the standards of emissions of pollutants by vehicles, in particular, the «Euro-6», «LEV-3», and «Tier-3» standards.

Among the standardized components of exhaust emissions (EG) of internal combustion engines in the EU, special attention is paid, in particular, to particles (PM) – one of the most harmful components in the composition of exhaust gases, nitrogen oxides (NO_x), total hydrocarbons (T.HC) and their non-methane parts (NMHC), carbon monoxide (CO), and other toxic substances that cause multibillion-dollar macroeconomic losses to society.

More stringent standards for emission standards, in turn, will require the development of appropriate new, more sensitive methods for determining mass emissions of pollutants.

A fundamentally insurmountable drawback of the standard method of sampling a constant volume is the generally high values of the EG dilution factor, which are obtained at most engine operating modes in test, in particular, driving cycles. In general, the high values of the EG dilution factor o are due to the need to establish a constant in time value of the flow rate of the mixture of EG and air, provided there is no moisture condensation, for the most loaded engine operation mode (among the entire set of modes in the test cycle). Therefore, the concentrations of individual pollutants (primarily carbohydrates) in diluted exhaust gases can be comparable with their concentrations in ambient air. This significantly complicates, and in some cases, in principle, makes it impossible to measure emissions of environmentally friendly cars that meet «Euro-6», «LEV-3», and «Tier-3» standards. It also limits the establishment of more progressive emission standards.

Thus, the urgent task is to find an alternative to the standard method of sampling a constant volume, which imposes fundamental restrictions on the determination of low emissions.

2. Literature review and problem statement

The laboratory determination of the specific mass emissions of pollutants by vehicles in accordance with the requirements of international technical regulations is carried out on the basis of the full-flow constant volume sampling method (CVS).

The constant volume sampling method is described in detail in the current technical regulations – UN Regulation No. 83, No. 49, No. 96, No. 40, No. 47 [1–5], US Regulations (CFR-40) [6], Global Regulation No. 2, No. 4, No. 11, No. 15 [7–10].

A fairly simple principle of operation of this method, described in the above sources, is to maintain a constant in time flow of a mixture of exhaust gas and air under conditions of rapid change during the test procedure, the flow of exhaust gas and concentrations of pollutants in it. According to the measured total consumption of the mixture of EG and air and the averaged concentrations of pollutants in it, their mass emissions are determined.

A general overview of methods for measuring pollutant emissions by vehicles is provided, in particular, in [11, 12]. Despite the partially-in-line emission determination technologies developed in recent years and certain inherent advantages, the in-line method provides the most reproducible results and remains essentially a reference.

This method well met the requirements of environmental standards of previous years. At the same time, the constant-volume sampling method imposes fundamental restrictions on the determination of low levels of mass emissions of pollutants by modern environmentally friendly vehicles, in particular, those using alternative types of motor fuel.

Limitations lie in the very principle of a constant volume sampling method. The minimum required value of the flow rate of the mixture of EG and air must be set in the absence of moisture condensation for the most loaded engine operation mode.

This flow rate, which remains constant throughout the test procedure for the driving (or motor) cycle, is too large for the modes of small and medium (partial) engine load, which account for a significant part of the time and emissions of pollutants.

Too high dilution factor of EG with air at partial engine load conditions under conditions of low concentrations of pollutants in raw EG results in concentrations of individual pollutants that are comparable to their concentrations in the air in the laboratory. This makes it impossible to measure them.

This problem complicates and even makes it impossible for individual emission components to effectively reduce the maximum permissible emission standards (can't be measured by the standard method), and limits the development of technical regulation in this area.

So, the development of new methods and technologies for determining specific mass emissions of pollutants is an urgent task.

It is known and such that today the method described in US Patent No. 5,337,595, issued August 16, 1994, "Subsonic venturi proportional and isokinetic sampling methods and apparatus" is widely used in practice in practice by eliminating the main drawback of the constant volume sampling method. [13]. According to this method, the test cycle is divided into several phases separated in time and for each phase their optimal flow rate of the mixture of exhaust gases and air is established, which is kept constant during this phase of the test.

The disadvantage of this method is that the change in the flow rate of the mixture must occur in the intervals between the individual phases of the test cycle, that is, with a temporary stop of the test process and measurement of pollutant emissions. But this is not always and not for each test cycle possible in principle.

In addition, modern test cycles contain multiple combinations in different phases of both full or close to full modes and light engine load modes. This is a significant limitation for using this method and overcoming the above main disadvantage of the constant volume sampling method.

Another well-known method described in US patent No. US 7,021,130 B2, issued April 4, 2006, "Method and device for the measurement of exhaust gas from internal combustion engines" [14]. Calculate the so-called smoothed value of the measured EG flow, which varies in accordance with the average values of EG instantaneous flow for a certain period of time. The rate of change is selected in accordance with the rate at which corresponding corrections can be made to the speed of the total flow of the mixture and the speeds of the sampling flows into elastic containers and through particle capture filters. The concentrations of pollutants averaged over the test cycle are measured in elastic containers, which are used to calculate mass emissions. In this case, the average dilution factor is set approximately the same during the test cycle.

The advantage of this method is to obtain, on average, close to optimal values of the EG dilution factor. But its disadvantages are:

1. The impossibility of determining, for example, hydrocarbon emissions for compression ignition engines (diesels) by the integrated method.
2. Limited opportunities for choosing the most optimal mode of EG dilution in each of the engine operation modes.
3. The introduction of additional uncertainty regarding the measurement results. This is due to measurement errors and tasks (maintaining) a constant dynamic change in the flow of the sum of EG and atmospheric air and gas sampling flows into elastic containers, to particle capture filters and the like.
4. Significant uncertainty regarding the measurement results in rapidly changing transient modes of engine operation, especially at peak loads, which are characteristic of modern test cycles.
5. The lack of important information on the results of the test regarding the distribution of specific emissions of pollutants for individual engine operating modes in the test cycle.

A study of the determination of low concentrations of pollutants is given in [15, 16]. But they do not propose a radical solution to the above problem.

The influence of various factors on the accuracy of measuring fuel consumption by the carbon balance method is given, in particular, in [17]. In [18], the components of the error in determining emissions in the laboratory equipment as a whole are presented. In [19], an error analysis of the mass emission measurement system is presented. These works show that one of the key factors is maintaining the minimum possible EG dilution factor and determining the concentration of pollutants in transition modes (that is, under conditions of a rapid change in the consumption of exhaust gases and concentrations of pollutants in them).

In [20], an intermittent sampling regime is proposed to increase the concentration of pollutants in a full-flow system during the testing of hybrids. Sampling management obviously allows for higher resolution measurements.

An example of calculating the instantaneous concentrations of pollutants in raw gas in transient engine operation using the measured concentrations in dilute gases in a full-flow tunnel is given in [21]. A study of the methods for the inverse calculation of instantaneous concentrations of pollutants in raw EG, including directly in the exhaust manifold of an engine with its measured concentrations in a diluted sample, is given in [22–24]. These studies prove the fundamental possibility and prospects of developing a new method of variable volume sampling. In particular, a method with integrated determination of mass emissions by instantaneous values of the flow rate of the mixture and the concentration of pollutants in it, reduced to the time of sampling.

The results of creating a prospective research full-flow system model EMMS-CVS-010 for determining low levels of mass emissions of pollutants from the exhaust gases of automobile engines are presented in [25, 26]. This equipment, unique in design and applied technology, is used today to determine whether Euro cars comply with environmental standards, carry out finishing work on new vehicle designs, research alternative motor fuels, determine fuel consumption by carbon balance method, etc. EMMS-CVS-010 is the first workable full flow system for determining mass emissions of pollutants created in the countries of the former Soviet Union.

Original technical solutions incorporated into the design of the EMMS-CVS-010 system made it possible to carry out, on its basis, the development of a new method for determining mass emissions of pollutants, namely, a variable-volume sampling method.

The variable volume sampling method, as shown in [26], makes it possible to bring the EG dilution factor closer to the minimum required value not only in one maximum load mode, but also in other engine operation modes during the test procedure. Partial load conditions account for the bulk of engine operating modes and a significant portion of pollutant emissions [1–10]. This allows to significantly increase the difference between the concentrations of pollutants in diluted exhaust gas and in ambient air. But this makes it impossible to apply a simple approach to the determination of mass emissions, as is done in the method of sampling a constant volume. The constant change in the flow rate of a mixture of EG and air requires the development of new approaches to the determination of mass emissions of pollutants.

3. The aim and objective of research

The aim of research is to create an improved technology for determining low levels of mass emissions of pollutants from exhaust gases of automobile engines.

To achieve this aim, the following objectives are set:

– to develop a new improved method for of variable volume sampling and to create an experimental full-flow system for determining mass emissions of pollutants from exhaust gases of automobile engines based on the concept of variable volume sampling;

– to explore the performance of the developed method.

4. Development of an improved method and experimental variable volume sampling system

The development of a full-flow technology for determining mass emissions of pollutants was carried out in [27]. It developed a new concept of variable volume sampling, which allowed to significantly increase the sensitivity and resolution of measuring mass emissions of pollutants.

Fig. 1 shows the main part of the research full-flow sampling system based on the universal constant volume sampling system (CVS) of the EMMS-CVS-010 model developed by the GosavtotransNIIproekt State Enterprise.

In Fig. 2, the research system of dynamic feeding into the mixing chamber EMMS-CVS-010 and measuring the flow rate of test gas mixtures is shown. It is assembled on the basis of the MT-010 universal particle emission analysis system, also developed at the GosavtotransNIIproekt State Enterprise. It is used as a precision generator of gas mixtures with a dynamic change in costs according to a given law.

Further development of this technology is to improve methods for determining the instantaneous values of mass emissions of pollutants in transient conditions.

Fig. 3 shows the functional diagram of the main elements of the system that implements the new proposed method of full-flow variable volume sampling to determine the mass emissions of pollutants from the exhaust gases of engines.

Fig. 1. Experimental full-flow sampling system based on the universal constant volume sampling system (CVS) of the EMMS-CVS-010 model developed by the GosavtotransNIIproekt State Enterprise

Fig. 2. Experienced system of dynamic feeding in the mixing chamber and measuring the flow rate of calibration gas mixtures

Fig. 3 shows:

1 – sample pipeline for supplying the full EG volume to the mixing chamber from the exhaust system of the engine;

2 – air filter;
3 – air conditioning system (option)
4 – inlet pipe for supplying atmospheric air to the system;
5 – elastic containers;
6 – system for sampling air into elastic containers;
7 – mixing chamber;
8 – tunnel;
9 – pipe sampling particles to capture filters;
10 – interchangeable particle capture filters;
11 – gas sampling system for particle capture filters;
12, 13 – gas outlet;
14 – system for measuring the amount of diluted exhaust gas;
15 – pipe sample particles;
16 – mixture conditioning system;
17 – sampling system of a mixture of high-temperature gas and atmospheric air;
18 – system for measuring the concentration of gaseous pollutants, contains in-line gas analyzers;
19 – measured concentration of pollutants in the sample;
20 – instantaneous flow rate of a mixture of EG and atmospheric air;
21 – unit for the inverse calculation of the current values of the concentrations of pollutants at the time of sampling from the main flow;
22 – calculated value of the concentration C_i of the pollutant (i) in the sample at the time of sampling from the main flow;
23 – block for the inverse calculation of the instantaneous flow rate of a mixture of EG and atmospheric air at the time of sampling from the main flow;
24 – calculated value of the flow rate Q at the time of sampling from the main flow;
25 – system for selecting and measuring the instantaneous flow rate of a mixture of EG and air is changed;
26 – pipe for sampling undiluted EG to the analyzer of carbon dioxide CO_2;
27 – high-speed CO_2 analyzer;
28 – measured CO_2 concentration in a sample of undiluted EG;
29 – unit for the inverse calculation of the current values of CO_2concentrations in a sample of undiluted gas at the time of sampling of gases from the gas supply line to the mixing chamber;
30 – calculated value of the CO_2 concentration in undiluted gas at the time of sampling of gases from the pipeline supplying the gas to the mixing chamber;
31 – calculated value of the CO_2 concentration in undiluted EG, reduced to the time of sampling the mixture by system 17;
32 – cylinder with a mixture of calibration gas mixtures (CGM) containing known concentrations of pollutants – carbon dioxide (CO_2), carbon monoxide (CO), propane (C_3H_8), nitrogen dioxide (NO_2), methane (CH_4), etc. ;
33 – system for dynamically feeding and measuring the CGM flow rate.

The proposed method of full-flow variable volume sampling to determine the mass emissions of pollutants from the exhaust gases of the engines and the system that implements it, works as follows:

The full exhaust gas flow from the exhaust system of the engine through the sample pipe 1 is supplied to the mixing chamber 7. Also, the cleaned in the air filter 2 and (optionally) conditioned air in the conditioning system 3 are supplied to the mixing chamber 7. At the same time, a sample of purified air comes from the air filter 2 through the system 6 to the elastic containers 5.

Subsequently, purified air from variable elastic containers 5 is used to adjust the results of measurements by gas analyzers of 18 concentrations of pollutants in the mixture of EG and air to exclude from the analysis some of the pollutants that enter the mixture with atmospheric air.

In the mixing chamber 7, the EG and atmospheric air are mixed, and then this mixture is fed into the tunnel 8, from which gas samples are taken through the pipe 9 to replaceable particulate filters 10 using the sampling system 11. Through the pipe 15, gas samples are taken to the particle number determination system 14.

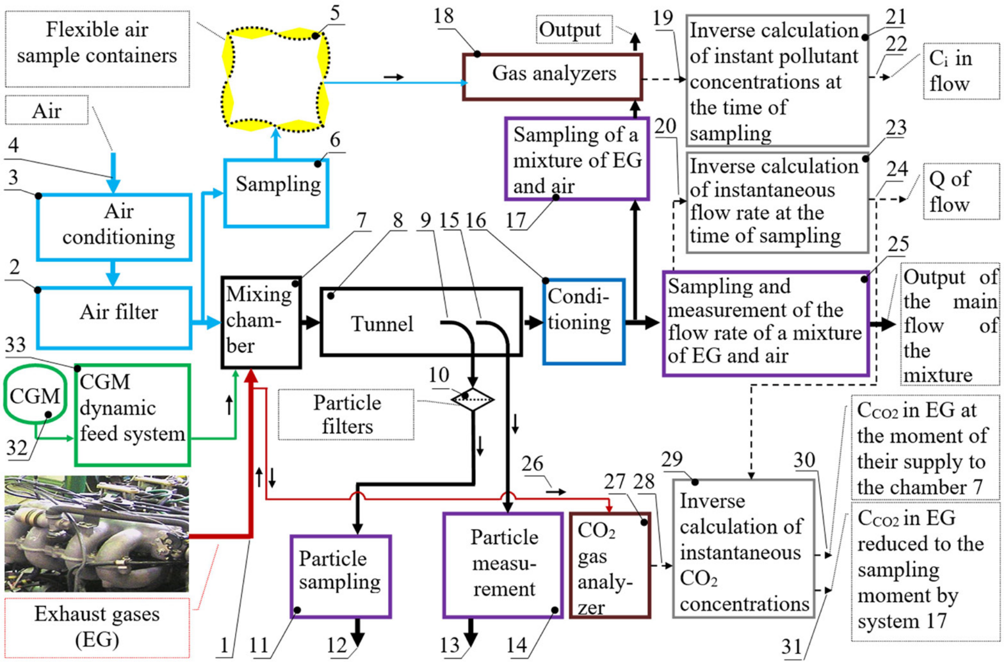

Fig. 3. Functional diagram of the main elements of the system, implementing a new method of full-flow variable volume sampling

The flow of the sample through pipelines 9 and 10 is set proportional to the total flow of the mixture of EG and atmospheric air at the entrance to the tunnel 8, equal to the sum of the flow of the mixture through its conditioning system 16 and the flows at the inlets of pipelines 9 and 15.

The flow through the conditioning system of the mixture 16 is equal to the sum of the flow through the system 25 and the system 17, with the exception of part of the flow, returns to the system 25 through the system 11, if the output 12 of the system 11 is connected to the input of the suction (selection) system 25 and measuring the total flow.

The total flow of the mixture of EG and air, equal to the flow at the entrance to the tunnel 8, is predominantly set by the system 25, taking into account a relatively small part of the flow, set by the systems 12, 14 and 17, which take samples.

The total flow of the mixture of EG and air causes, therefore, the EG dilution factor.

System 17 feeds the sample to system 18 for continuous analysis of the concentrations of pollutants in the mixture.

The information signal 19 of the values of the measured concentrations of pollutants in the sample is supplied to the block 21 inverse calculation of the current values of the concentrations of pollutants at the time of sampling from the main flow. The output 22 of which is the calculated value of the concentration C_i of the pollutant (i) in the sample at the time of sampling from the main flow.

The information signal 20 values of the flow rate of the mixture of EG and air is supplied to the block 23 inverse calculation of the flow rate of the mixture of EG and air at the time of sampling from the main flow. The output 24 of which is the calculated value of the flow rate Q at the time of sampling from the main flow.

The block 21 for the inverse calculation of the current values of the concentrations of pollutants at the time of sampling from the main flow and the block 23 for the inverse calculation of the flow rate of the mixture of EG and atmospheric air at the time of sampling from the main flow contain a description of the functions that determine the delay time of the information signal. This delay time is due, in particular, to the time the sample is transported through pipelines and other elements of the sampling and sample preparation systems, the time constant (dynamic response properties) of the system for measuring concentrations of pollutants. Partial mixing of time-distributed sample fragments with various concentrations of pollutants in pipelines and elements of the sample preparation system is also taken into account.

Blocks 21 and 23 use the memory record of discrete values distorted through the above phenomena of information signals at the input. Then, based on the mathematical description of these phenomena, the information signals relative to the instantaneous values of the concentrations of pollutants at the outlet of the gas analyzers and the flow rate of the mixture of EG and air are reproduced in the original and synchronized time.

EG sample is taken from the point of attachment of the EG supply pipe to the mixing chamber (7) through a pipe (26) and is supplied to a high-speed CO_2 analyzer (27). An information signal (28) of the measured concentrations of carbon dioxide CO_2 in the EG sample is fed to block (29) for the inverse calculation of the current values of CO_2 concentrations in the EG sample at the time of sampling of gases from the pipeline supplying the EG to the mixing chamber. At the output (30) of this block, the value of CO_2 concentrations at the time of sampling the gases from the gas supply line to the mixing chamber is calculated.

Block (29) uses the recording of discrete values of distorted values through the above phenomena of the information signal at the input. Further, based on the mathematical description of these phenomena, the original information signal (30) is reproduced from the instantaneous values of the concentration of carbon dioxide CO_2 in the gas at the time of sampling of gases from the gas supply line to the mixing chamber.

The time of transporting the pollutants in the exhaust gas to the place of sampling by the system (17) of the gas mixture sample by the information signal of the flow rate of the gas and air mixture is determined (24). In this case, take into account the total volume of the tunnel (8) and system (16) and the volume of other pipeline elements from the place of entry of the exhaust gas flow in the mixing chamber (7) to the place of sampling of the gas mixture by the system (17) in block (29). According to the method of variable volume sampling, at present it is not a constant value, since the flow rate of the mixture of EG and air and the speed of this flow in the pipelines is not constant. Thus, at the output (31) of block (29), the value of CO_2 concentrations in the raw EG is calculated; it is reduced to the moment of sampling the mixture by system 17.

Dynamic autocalibration of the system is carried out by supplying from the cylinder (32) a calibration gas mixture (CGM) containing known concentrations of pollutants – carbon dioxide (CO_2), carbon monoxide (CO), propane (C_3H_8), nitrogen dioxide (NO_2), methane (CH_4) things like that. CGM is fed through the system (33) into the mixing chamber (7) at a rate that is changed according to a known periodic function. Thus, a mass flow of normalized pollutants with a known value of its instantaneous flow rate at each moment of time is added to the flow of mass emissions of pollutants through the system coming from the EG. That is, the mass flow of the sum of pollutants in the system is thus a modulated flow from the system (33).

The calculation of the actual value of the EG dilution factor is carried out separately at each elementary time step as follows:

$$DR=\frac{0.5\left(C_{\mathrm{CO_2}(R)e(j-1)}+C_{\mathrm{CO_2}(R)e(j)}\right)\times\dfrac{0.5\left(Q_{f(j-1)}+Q_{f(j)}\right)}{t_{(j)}-t_{(j-1)}}}{\dfrac{0.5\left(Q_{n(j-1)}+Q_{n(j)}\right)}{t_{(j)}-t_{(j-1)}}\times0.5\left(C_{\mathrm{CO_2}(M)e(j-1)}+C_{\mathrm{CO_2}(M)e(j)}\right)-\dfrac{0.5\left(Q_{s(j-1)}+Q_{s(j)}\right)}{t_{(j)}-t_{(j-1)}}\times C_{\mathrm{CO_2}}\,(\mathrm{CGM})},\quad(1)$$

where DR – the actual value of the EG dilution factor;

$C_{\mathrm{CO_2}(R)e}$ – the measured CO_2 concentration in raw EG, at the beginning $C_{\mathrm{CO_2}(R)e(j-1)}$ and at the end of the elementary step $C_{\mathrm{CO_2}(R)e(j)}$, expressed in volume percent (information signal (31) by the instantaneous values of the concentration of carbon dioxide CO_2 in raw EG, reduced to the moment of sampling the mixture by system (17));

$0.5\left(C_{\mathrm{CO_2}(R)e(j-1)}+C_{\mathrm{CO_2}(R)e(j)}\right)$ – the average value of CO_2 concentration in raw EG at the elementary step j, reduced to the moment of mixture sampling by system (17);

$C_{CO_2(M)e(j)}$ – the measured CO_2 concentration in diluted EG, at the beginning $C_{CO_2(M)e(j-1)}$ and at the end of the elementary step $C_{CO_2(M)e(j)}$, expressed in volume percent (information signal (22) by instantaneous CO_2 concentration in the sample at the time of sampling from the main flow);

$0.5\left(C_{CO_2(M)e(j-1)}+C_{CO_2(M)e(j)}\right)$ – the average value of CO_2 concentration in diluted EG at the elementary step j at the time of sampling from the main flow;

$C_{CO_2}(\text{CGM})$ – the known CO_2 concentration in underground gas storage in a cylinder (32), which is supplied through system (33), expressed in volume percent;

$\frac{0.5\left(Q_{n(j-1)}+Q_{(\ )}\right)}{t_{(j)}-t_{(j-1)}}$ – the volume of the total flow of diluted exhaust gas taken during the elementary step, expressed in liters and adjusted in accordance with standard atmospheric conditions;

Q_f – the instantaneous flow rate of the total diluted exhaust gas flow at the beginning $Q_{f(j-1)}$ and at the end Q_{fj} of the elementary step, expressed in l/s and adjusted in accordance with standard atmospheric conditions;

$\frac{0.5\left(Q_{s(j-1)}+Q_{s(j)}\right)}{t_{(j)}-t_{(j-1)}}$ – the volume of CGM flow that is supplied to the chambers (7) during the elementary step, expressed in liters and adjusted to standard atmospheric conditions;

Q_s – the instantaneous flow rate of underground gas storage at the beginning $Q_{s(j-1)}$ and at the end $Q_{s(j)}$ of the elementary step, expressed in l/s and adjusted in accordance with standard atmospheric conditions;

t – the time (s) at the beginning $t_{(j-1)}$ and at the end of the elementary step $t_{(j)}$.

The concentration of the pollutant in the diluted exhaust gas is adjusted for the already existing amount of pollutant in the air as follows:

$$C_i=C_e-C_d\times\left(1-\frac{1}{DR}\right), \tag{2}$$

where C_i – the concentration of the i-th pollutant in diluted EG, expressed in ppm and adjusted for the amount of the i-th substance that is already in the air; C_e – the measured concentration of the i-th pollutant in diluted EG, expressed in ppm; C_d – the concentration of the polluting i-th substance in the air used for dilution, expressed in ppm,

According to this method, the total mass emissions of gaseous pollutants M_{Si}, the mass of emissions of the i-th pollutant in grams at the elementary step j with the CGM flow M_{ki} and mass faseous pollutant emissions from EG M_i as follows:

$$M_{Si(j)}=\frac{0.5\left(Q_{f(j-1)}+Q_{f(j)}\right)}{t_{(j)}-t_{(j-1)}}\times d_i\times$$
$$\times k_{h(i)}\times 0.5\left(C_{i(j-1)}+C_{i(j)}\right)\times 10^{-6}, \tag{3}$$

$$M_{ki(j)}=\frac{0.5\left(Q_{k(j-1)}+Q_{k(j)}\right)}{t_{(j)}-t_{(j-1)}}\times d_i\times k_{h(i)}\times Ce(\text{CGM}), \tag{4}$$

$$M_{i(j)}=M_{Si(j)}-M_{ki(j)}, \tag{5}$$

where $M_{Si(j)}$ – the total mass of emissions of the i-th pollutant in grams at the elementary step j;

$M_{i(j)}$ – the mass of emissions of the i-th pollutant in grams at the elementary step j with exhaust gases;

$M_{ki(j)}$ – the mass of emissions of the i-th pollutant in grams at the elementary step j with the CGM flow;

$\frac{0.5\left(Q_{f(j-1)}+Q_{f(j)}\right)}{t_{(j)}-t_{(j-1)}}$ – the volume of the total diluted exhaust gas flow (mixture of exhaust gases and atmospheric air), the elementary flow is selected pitch expressed in liters and adjusted to standard atmospheric conditions;

d_i – the density of the i-th pollutant in g/l under standard atmospheric conditions);

$k_{h(j)}$ – the value of the humidity correction coefficient at the elementary step j used to calculate the mass of emissions of nitrogen oxides NO_x. The moisture correction factor is calculated as defined in the above standards;

C_i – the concentration of the i-th pollutant in diluted exhaust gases at the beginning $C_{i(j-1)}$ and at the end of the elementary step $C_{i(j)}$. It should be adjusted for the already existing amount of pollutant in atmospheric air according to equation (2) according to the current measured values of the concentrations of components from the composition of diluted gases that enter it, and their concentrations in the air. The latter are determined from samples taken in elastic containers (bags) during various phases (fragments) of the test cycle, or by the results of their flow measurement, expressed in ppm;

$0.5(C_{i(j-1)}+C_{i(j)})$ – the average concentration of the i-th pollutant at the elementary step j;

$\frac{0.5\left(Q_{k(j-1)}+Q_{k(j)}\right)}{t_{(j)}-t_{(j-1)}}$ – the volume of CGM flow that is supplied to the chambers (7) during the elementary step, expressed in liters and adjusted to standard atmospheric conditions;

Q_c – the instantaneous flow rate of underground gas storage at the beginning $Q_{c(j-1)}$ and at the end $Q_{c(j)}$ of the elementary step, expressed in l/s and adjusted in accordance with standard atmospheric conditions;

$C_{e(\text{CGM})}$ – the known concentration of the corresponding pollutant in the CGM facility in the cylinder (32), which is supplied through the system (33), expressed in ppm.

A dynamic series of data on total mass emissions of gaseous pollutants M_{Si}, mass emissions of gaseous pollutants with exhaust gases M_i, mass emissions of pollutants with an CGM flow M_{ki} is determined in the process of post-processing data. These data are then used to set up the transfer functions described in blocks (21), (23), (29), based on the law of conservation of mass, thereby performing auto-calibration of the system.

The total mass of emissions of the i-th pollutant in grams per test procedure is determined as the sum of the emissions at each elementary step:

$$M_{i(t)}=\sum\nolimits_{j=1}^{n}M_{i(j)}, \tag{6}$$

where $M_{i(t)}$ – the mass of emissions of the i-th pollutant in grams per test procedure; $M_{i(j)}$ – the mass of emissions of the i-th pollutant in grams at the elementary step j; n – the number of elementary measurement steps per test procedure.

The information signal (30) is recorded by the instantaneous values of CO_2 concentrations in raw gas at the moment of gas sampling from the gas supply line to the mixing chamber, and the concentrations of other pollutants in raw gas at the time of their supply to the mixing chamber (7). It is of interest for research on technologies for controlling emissions of pollutants and development work on the creation of new types of equipment – engines and vehicles.

The calculations of the concentrations of other pollutants in raw EG ($C_{i(R)}$, ppm) at the time of their supply to the mixing chamber (7) are as follows:

$$M_{Si(j)}=\frac{M_{i(j)}\times DR}{\frac{0.5\left(Q_{f(j-1)}+Q_{f(j)}\right)}{t_{(j)}-t_{(j-1)}}\times d_i\times k_{h(i)}\times 10^{-6}}. \qquad (7)$$

The calculated values are synchronized in time with the moment of entry of pollutants in the mixing chamber (7). The time difference is the phase shift of the signals at the outputs (31) and (30) of the block (29).

According to this method, the flow rate of gas samples through filters for trapping particles and at the entrance to the device for determining their quantity is changed directly proportional to the change in flow rate of the mixture of EG and air. The calculation of particle emissions is determined in the same way as for the conventional method of sampling a constant volume.

Thus, the current mass emissions of pollutants are calculated by time-synchronized instantaneous values of concentrations and instantaneous values of the flow rate of the mixture of EG and air. The value of the EG dilution factor is determined by the ratio of the measured concentration of carbon dioxide (CO_2) in the raw EG, reduced to the moment of sampling the mixture from the exhaust gas and air, and the measured concentration of CO_2 in the diluted EG determined at the time of sampling from the main flow of this mixture. CGM containing known concentrations of pollutants is also supplied to a mixing chamber in which EG and air are supplied, and the CGM volume supplied to the mixing chamber per unit time is measured with a flow rate that is varied by a periodic function. This is used to determine the transfer functions of the inverse calculation of the instantaneous flow rate of a mixture of EG and air and the current values of the concentrations of pollutants at the time of sampling. Mass emissions of gaseous pollutants from exhaust gas are calculated as the difference between the total mass emissions of pollutants and the mass emissions of pollutants imparted with the CGM flow.

5. Research results of the working capacity of the developed method

Fig. 4 shows an example of determining a new method of emissions in the driving cycle of a car.

Fig. 5 shows an example of a change in the test cycle of the flow rate of a mixture of EH and air and the dilution factor DF. In this case, the minimum flow rate for partial load modes is established, which increases as the engine load increases.

Fig. 6 shows an example of comparing changes in the dilution factor test cycle DF for a constant volume sampling method (CVS) and a variable volume sampling method (VVS). According to the latter, the dilution factor for partial engine load conditions is substantially lower and closer to the optimum.

Fig. 4. Example of VVS determination of emissions in the driving cycle of a Mazda 6 passenger car with a positive-ignition engine

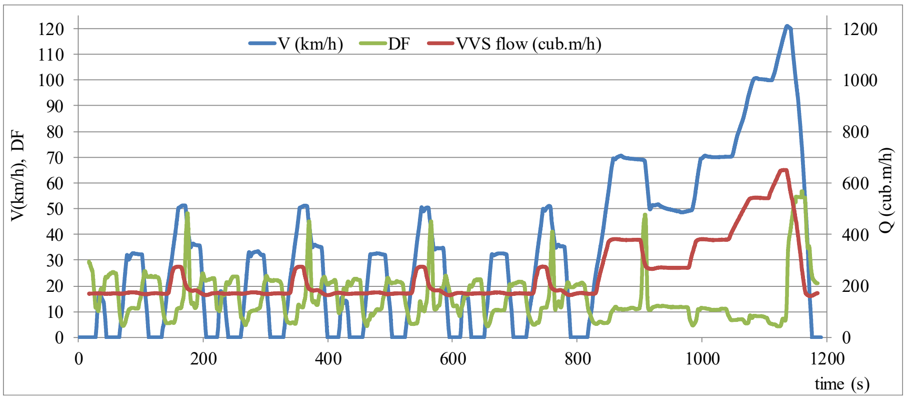

Fig. 5. An example of a change in the test cycle of the flow rate of a mixture of EG and air and the dilution factor DF

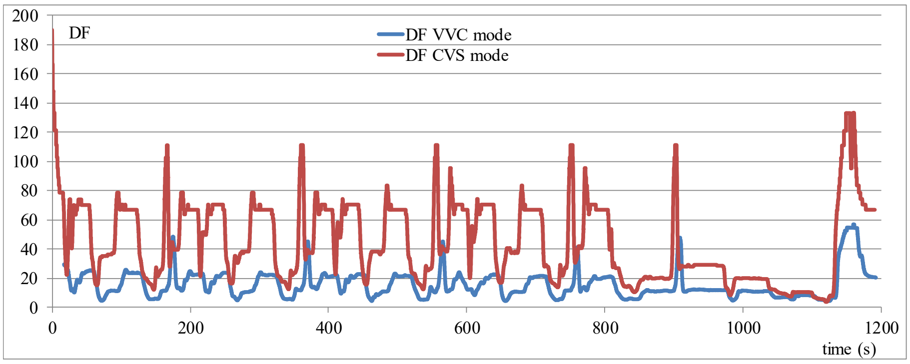

Fig. 6. Example of comparing changes in the test cycle of the dilution factor DF for the constant volume sampling method (CVS) and variable volume sampling method (VVS)

Fig. 7 shows an example of a change in pollutant concentrations in a driving cycle using the standard constant volume sampling method (CVS). It is possible to see peak concentrations in the “problem” sections of the driving cycle. But on most partial load modes, the standard method is no longer sufficiently informative. The concentration of pollutants in diluted exhaust gases can be comparable with their concentrations in ambient air.

Fig. 8 shows an example of a change in pollutant concentrations in a driving cycle using variable volume sampling (VVS). According to the new method, as can be seen from the graphs of changes in hydrocarbon concentrations in Fig. 7, 8, they get 4–5 times more corrected concentrations of pollutants in the sample of diluted EG, and therefore higher resolution.

This makes it possible to measure even mass emissions that are beyond the resolution of the standard method of sampling a constant volume, both in the whole driving cycle and in its individual modes. The latter is of significant interest to car manufacturers in the process of finishing work on new vehicle designs.

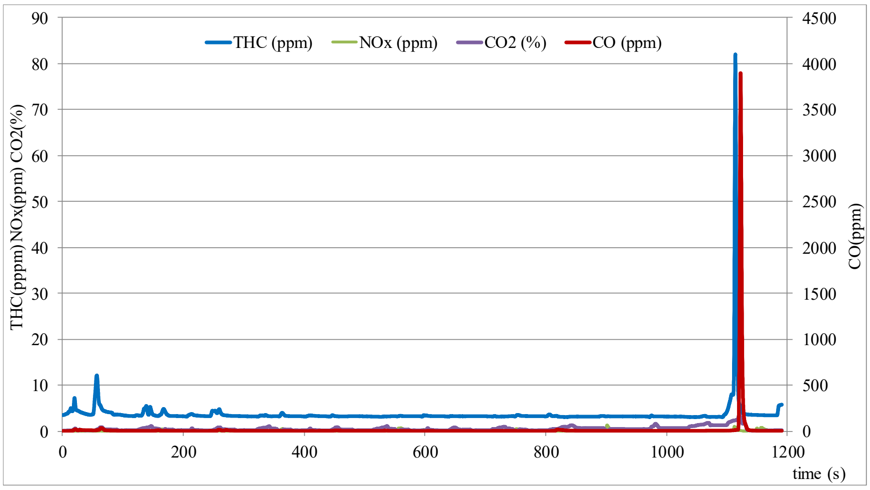

Fig. 7. An example of a change in the concentrations of pollutants in a driving cycle using the standard constant volume sampling method (CVS)

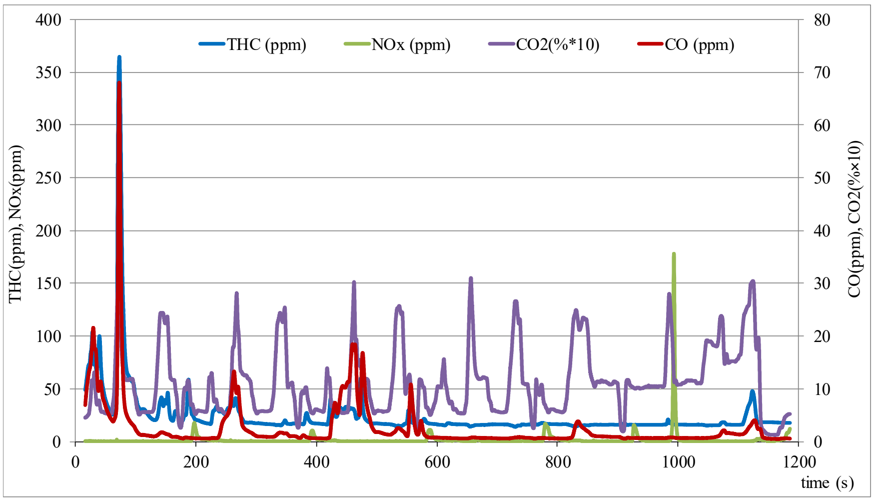

Fig. 8. Example of changing concentrations of pollutants in a driving cycle by variable volume sampling (VVS)

Verification of the new method was carried out by comparing the calculated (carbon balance method) and directly measured fuel consumption by cars in driving cycles.

The difference between the directly measured fuel consumption (using a flow meter) and the calculated (method of carbon balance for certain mass emissions of pollutants) fuel consumption does not exceed ±3.5 %. This is a satisfactory result, taking into account, in particular, the measurement uncertainty in the dynamics of rapidly changing concentrations of pollutants, the flow rate of diluted exhaust gas, fuel consumption, and the determination of carbon content in the fuel.

Since the commissioning of the research full-flow sampling system based on the universal constant volume sampling system (CVS) of the EMMS-CVS-010 model, more than 1,500 vehicle tests have been carried out on it, in particular, to determine compliance with Euro environmental standards. The publications [29, 30] provide separate summary results of these tests. The EMMS-CVS-010 system is used both to determine Euro-0 emissions and emissions, which are significantly less than the limit values established by Euro-6 standards with the latest amendments. In particular, the new technology, due to its greater information content and resolution, is used by car manufacturers to carry out finishing work in the development of new cars.

6. Discussion of the results of the development and implementation of a new method of variable volume sampling

New in the method, which was proposed in [26], and further developed in this work, is, in particular, that:

1. Mass emissions of pollutants are determined integrally as the sum of the current mass emissions for each elementary time step, determined by the time-synchronized instantaneous values of concentrations and instantaneous flow rates of the mixture of EG and air (as described in section 4, and the scheme shown in Fig. 3).
2. The flow of the mixture of EG and air is constantly changing at a speed less than the rate of change of the EG flow, so that it provides the highest possible concentration of pollutants in the mixture of EG and air, and also minimizes the measurement uncertainty during transient conditions. Accordingly, increase its relation to the concentrations of pollutants already contained in the air.
3. Under the conditions of variable volume sampling, the possibility of determining the emissions of hydrocarbons and nitrogen oxides for compression ignition engines by the integrated method is retained.
4. The method allows to maximally compensate for the introduced additional uncertainty regarding the measurement results due to measurement errors and tasks (maintenance) of a constant dynamic change in the flow of the sum of exhaust gases and atmospheric air. This is due to minimizing

the dilution of exhaust gases and synchronizing the time of information signals on the concentrations of pollutants and the flow rate of the gas mixture. This is especially true in transient modes of engine operation, changing rapidly, which account for most of the mass emissions of pollutants in test cycles.

5. Obtain important information on the distribution of specific emissions of pollutants for individual engine operating modes in the test cycle.

6. Carry out dynamic auto-calibration of the system for measuring mass emissions of gaseous pollutants directly during the measurement process. That is, this happens without interrupting the test of the engine or vehicle, simultaneously with the determination of the instantaneous actual EG dilution factor.

7. The instantaneous values of the concentrations of pollutants directly in the raw EG are also determined.

8. In general, radically improve the sensitivity, resolution, accuracy and information content of measurements.

The integrated determination of mass emissions of pollutants with instantaneous values of the flow rate of a mixture of EG and air and concentrations naturally entails the introduction of additional uncertainty. At the same time, this allows to significantly increase the difference between the concentrations of pollutants in diluted exhaust gas and in ambient air. As shown above, this is justifiable when measuring low emissions.

However, for measuring exclusively fuel consumption by automobiles using the carbon balance method, the lion's share of which is allocated through CO_2, the standard method of constant volume sampling usually provides better results.

The disadvantage of the new method is the complexity of its implementation. But this is offset by the above benefits. Fundamentally new possibilities have been obtained for measuring, with practical accuracy, the mass specific emissions of pollutants by forced-ignition engines and diesel engines of modern and promising low-emission vehicles. Accordingly, it was possible to install in the future more advanced environmental requirements for vehicle engines.

Work is ongoing to further improve this technology.

The standard method for sampling a constant volume to determine the mass emissions of pollutants is called the "method of sampling a constant volume." And the system that implements it is commonly called the "constant volume sampling system" or the "Constant Volume Sampling system" (abbreviated CVS system) in international English.

Therefore, by analogy, the alternative method described above for a full-flow sampling of a precisely variable volume for determining mass emissions of pollutants from engine exhaust gases is proposed to be called the "variable volume sampling method". The corresponding system that implements it is proposed to give the name "international sampling system of variable volume" or "Variable Volume Sampling system" (abbreviated VVS system) in international English.

7. Conclusions

1. A dynamic method for sampling of variable volume has been developed, for which a patent for the invention has been obtained [28]. An experimental full-flow system has been created for determining the mass emissions of pollutants from automobile engine exhausts; it implements the concept of sampling of variable volume.

2. The efficiency of the full-flow variable volume sampling method is proved by comparing the calculated (carbon balance method) and directly measured fuel consumption by cars in driving cycles. The difference between the directly measured and calculated (for certain mass emissions of pollutants) fuel consumption does not exceed ±3.5 %. This is a satisfactory result, taking into account, in particular, the measurement uncertainty in the dynamics of rapidly changing concentrations of pollutants, the flow rate of diluted exhaust gas, fuel consumption, and the determination of carbon content in the fuel.

Thanks to sampling of variable volume, on average, 4–5 times more concentration of pollutants in the sample of diluted exhaust gas is obtained. Thus, the new method allows even mass emissions that are beyond the resolution of the standard method of sampling a constant volume to be measured, both in the whole driving cycle and in its individual modes. The latter is of considerable interest and is used by car manufacturers in the process of finishing work on new vehicle designs.

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